Disruptions And ELMs: Questions That Need Answers Before DEMO

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The aim of this White Paper is to offer a list of specific questions that will need to be answered before proceeding with a DEMO for the two issues of disruptions and ELMs. Each of the individual questions is organized around, and follows from, a general question or theme. Although partial answers to some questions are already known, no attempt is made here to elaborate what is known but some comments are given in italics. Neither are the questions are intended to be exhaustive. But they should be addressed by any thrust directed at disruption and ELM issues or power loads. Finally, some general comments on strategies for solving these kinds of issues are discussed.

Disruption Limits, Avoidance, Mitigation and Recovery

The occurrence of disruptions is one of the crucial problems facing the tokamak vision of an economically viable fusion reactor. In a commercial reactor or DEMO, events that can cause catastrophic failure of internal components will need to be essentially non-existent. This does not imply that all disruptions must be eliminated; even in non-tokamak alternatives, some disruptions or 'off-normal events' will be unavoidable. The key questions then revolve around what are the limits that should not be exceeded, and when disruptions do occur, what can be done to mitigate them and what needs to be done to fully recover from them. Specifically, the questions are:

(i) What are the disruptions limits:

  a) How do we translate these into design guidelines for say a DEMO?
  b) Where is the design point relative to the limits?
  c) Can the likelihood of disruptions be quantified in a deterministic versus statistical sense?
     Disruptions have specific causes. If we can predict the occurrence of causes, then we can predict the impending occurrence of disruption.
  d) What level of control over the discharge is required to maintain the requisite level of confidence in disruption avoidance?
     A workable discharge scenario needs a finite margin to allow for control 'noise', lack of ideal measurement and small real-world variances. How much, depends on the robustness of the scenario, the degree of active control possible. There has been success in operating within a few percent of the ideal MHD beta limit without disruption. But the limit can change whenever the machine or wall conditions change.
  e) Assuming there are no hardware failures or hardware induced disruptions, how much confidence is there that the design point will be disruption free over the length of the pulse or through steady state?
  f) What other time scales, longer than plasma evolution times, are important for maintaining a disruption free state:
     i. Are wall saturation time scales relevant?
     ii. Are there chemistry interaction time scales that are relevant in the longer term?

   g) What does 'disruption-free' really mean in steady state?
      If steady-state is really steady or stationary, with some finite margin against disruption onset, then the discharge will be 'disruption-free' unless external conditions intervene. External conditions involve hardware reliability, unpredictable events (falling flakes, vacuum window breaks, hardware and/or control system failures) and Murphy's Law. The basis for predictions of these external aspects is meager. Some hardware problems can be reduced or solved by redundancy or 'fail-safe' strategies but other failures may be fatal to continuing plasma operations.

(ii) Can unavoidable hardware induced disruptions be mitigated:
   a) What are the maximum forces that can occur during a disruption?
   b) Can currents in external structures be managed?
   c) Can the mitigation be done in time:
      i. Is pre-emptive mitigation possible and/or feasible?
      ii. Is after-onset mitigation necessary and/or effective?

      The consequences of many types of hardware failures may be slow enough to invoke an avoidance, soft-landing or mitigation action. In some cases, avoidance actions can be taken; in other cases, pre-emptive and or after-onset mitigation can be effective at reducing some, but not necessarily all, disruption consequences.

      After-onset mitigation is more problematical and will not necessarily be 100% effective.
   d) What are the consequences to walls, divertors, and nearby hardware (e.g. antennas)?
   e) What design and engineering requirements are needed for mitigation of unavoidable disruptions?
   f) What is the toroidal and poloidal distribution of the energy dump during a disruption:
      i. Is it localized toroidally and/or poloidally?
      ii. How directed is the radiation?
      iii. Runaways are clearly localized but can the direction be predicted?

(iii) What options are available for disruption recovery:
   a) What are the after-effects of a disruption:
      i. Will dust showers be a problem?
      ii. What are the consequences of dust in the machine afterward?
      Dust showers are observed after roughly half the VDEs in DIII-D.
   b) What are the overall consequences of rapidly dumping large power levels from a huge volume:
      i. Can the approximately Terawatts of power expected during a 1 msec disruption be handled?
      ii. How can this large energy be removed from the system?
      iii. Can mitigation techniques intended to rapidly cool the plasma work over the large volumes expected in ITER and DEMO?
   c) What effects do disruptions have on the surrounding material surfaces:

        i. Possible damage to limiters, antennas, wall coatings, divertor surfaces?
        ii. Is erosion localized or not?

(iv) Is the current knowledge base sufficient to predict the occurrence and effect of runaway electrons:

  a) How are runaway electrons generated?
  b) Where do runaways go?
  c) What are the effects of the runaways on external components:
      i. How do runaways interact with the walls?
      ii. Can sensitive structures be protected from runaways?
      iii. What are the effects of the heat flash versus radiation? Do they comprise single radiation flashes or are there multiflashes from runaways?
      iv. Does the runaway population filament or remain an intact localized beam?
  d) How does the amplification factor scale to DEMO?

(v) What differences exist between nonaxisymmetric beta-induced disruptions and axisymmetric vertical displacement events (VDEs)?
Beta limit disruptions appear to generate significant runaways on a fast time scale. VDEs are much slower but the current channel generally remains intact creating large forces and dumping the current into the structure, and also generating runaways.

(vi) What are the tradeoffs in requiring a disruption tolerant blanket structure:

  a) On the design?
  b) On maintenance schemes?

(vii) What additional issues arise from the increased likelihood of disruptions during startup and current rampdown?

ELMs, ELM control, and divertor and wall loading during ELMs

ELMs are ubiquitous in H-mode, and while relatively benign in current experiments, pose a serious threat to the success of thermonuclear fusion. In ITER, even small ELMs may not be tolerable and in DEMO the issues are sure to be significantly more challenging. The questions revolve around what are the limits for ELM onset and can the onset be predicted, can ELM size be reduced or controlled, and what are the consequences in terms of the energy and power loads on the walls and divertor. The key questions are then:

(i) Can ELMs be predicted?

  a. Can size frequency and onset be predicted?
  b. Is it the scaling in power flux or the total energy that is important?
  There is a need to distinguish power flux and energy flux and the scaling for both of these fluxes needs to be known. Scaling of flux expansion is needed as well but scaling of the power flows is the more important issue. A database of $\delta W/W_{ped}$ may provide some information.

(ii) What are the predictions for ELMs for a given design point:

   - a) What are the consequences of ELMs on divertor and wall loads?
   - b) Are divertor and wall modifications required for some design points?

(iii) Can the ELMs be controlled by discharge control:
   - a) Can cross section shaping be used to induce small more frequent ELMs?
   - b) Can seeding of the edge by impurities be used to induce small ELMs?

(iv) Can recently identified options for reducing ELM size or ELM-free operation be applied in DEMO:
   - a) Will nonaxisymmetric coils work to control ELMs:
      - i. Will this be demonstrated by ITER?
      - ii. If they are necessary or desirable, are they practical?
      - iii. What design features should such coils have?
      - iv. How close will they need to be: Do the need to be inside the first wall or can they be outside or even outside the toroidal field coils?
      - v. Will one be able to extrapolate from current experiments?
      - vi. Will dedicated experiments be needed?
   - b) Will other ELM-free operational regimes be absolutely necessary:
      - i. Quasi-H Mode (QH-Mode)?
      - ii. Enhanced D-alpha Mode (EDA)?
      - iii. L-Mode?
   - c) How much degradation in performance will these entail?

(v) Is there a gain from using a double null divertor:
   - a) What is the gain in plasma performance?
   - b) What is the reduction in loads on each divertor?
     A factor two reduction in heat loads is theoretically possible but will not be automatically realized in practice since the conditions for balancing the divertor loads are not easy to maintain.

(vi) What is of the distribution of the energy dump from ELMs:
   - a) Between the first wall and the divertor?
   - b) What is the toroidal and poloidal distribution:
      - i. Is it localized toroidally?
      - ii. Is it localized poloidally?
   - c) How does the energy distribution differ between ELMs and during an ELM?
   - d) Are MARFEs an issue?
     MARFES result in collapse of the core. A possible high payoff research issue is to try to disconnect the MARFEs from the core plasma.

(vii) How can the energy from and ELM be extracted:
   - a) From the wall and blanket?
   - b) From the divertor?
     Energy will at least need to be handled even if not converted to useful forms and used as part of the power output of the reactor.

(viii) What additional maintenance issues arise as a result of divertor loads from ELMs:

a) What are the replacement rates for various modules?
b) How localized is the erosion on divertor plates?

(ix) Does a radiative divertor solution exist for DEMO:

a) Can complete radiative divertor detachment be avoided?
The window of partial detachment is expected to be small to nonexistent for ITER and more so for DEMO.

b) What volume will the radiative divertor region need to be to handle the ELM power flow?
There is a real concern that the volume necessary for dissipating the envisaged power levels may be so large that it destroys the core performance.

A General Comment on Solution Strategies

The solutions for both the disruption and the ELM issues can both be categorized into three separate strategies. These have both advantages and disadvantages and the tradeoffs need to be evaluated:

i. Live and deal with the consequences as they occur:
Generally, in addition to physics information on the fluxes etc., this option requires engineering solutions, which may or may not be forthcoming. For the disruption issue it includes a disruption-tolerant blanket structure, taking account and designing for the energy and power distribution, the disruption recovery solutions, and accounting for runaways, etc. For ELMs and the divertor it involves solutions such as double null divertors, radiative divertor, with radiating core and mantle, divertor designs, and possibly MARFEs, etc.

ii. Limit or mitigate the effect by reducing the size of the perturbation:
This involves physics solutions such as mitigation, etc for the disruption issue and for the ELM issue it involves all of the ELM control options, including non-axisymmetric coils, etc.

iii. Eliminate the phenomena entirely:
This option involves physics solutions that generally require reduced performance. For the disruption issue, this includes operation away from the stability limits, and possibly special, carefully designed startup and rampdown scenarios. For the ELM and divertor issue, this includes the ELM-free operation options, including perhaps nonaxisymmetric coils, all of which require some performance loss, as well as possible options for L-mode edge operation (with or without an L-mode core), which may require considerable degradation in performance.

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